# The Hardware/Software Interface

## Structs and Alignment

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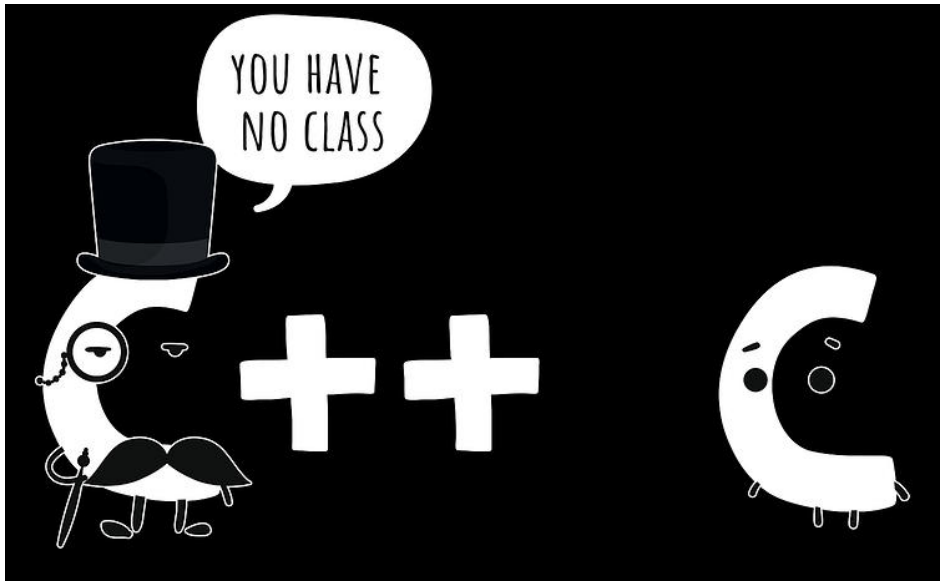


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# Relevant Course Information

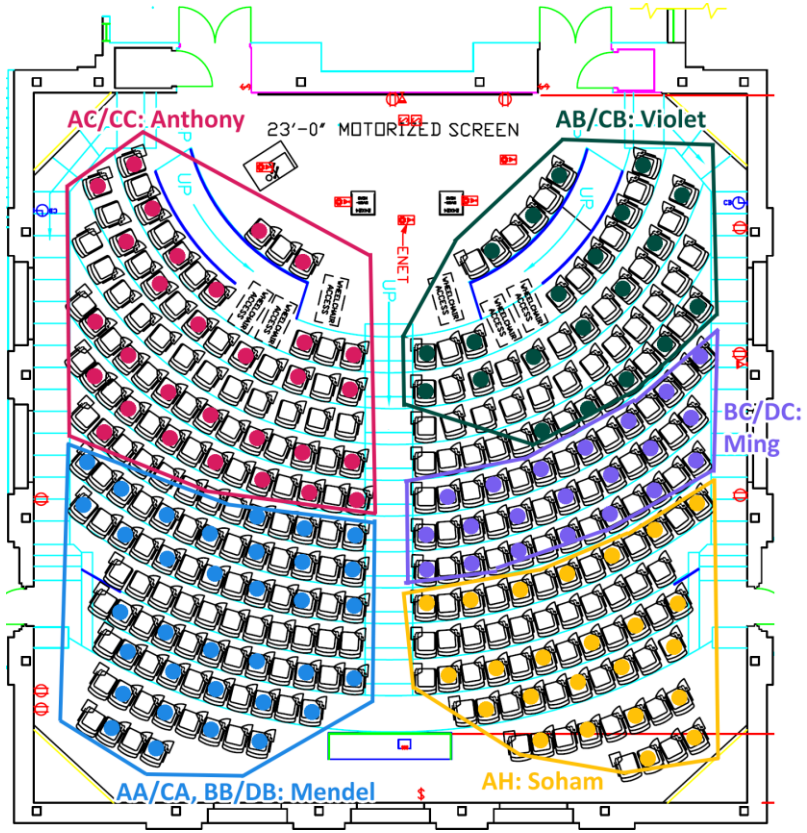
- Lab 2 due tonight
- Lab 3 released next Wednesday (10/29)
  - A shorter lab, due Friday, 11/7
- HW13 due next Wednesday (10/29), HW14 due next Friday (10/31)

- **Midterm** (Monday 10/27, 5:30-6:40 pm)
  - Midterm details Ed post #296
    - Come early to get exam and settle in
    - Make a cheat sheet! – two-sided letter page, *handwritten*
  - Review session (Ed post #301) tonight at 4:30 pm in CSE2 G01 and on Zoom

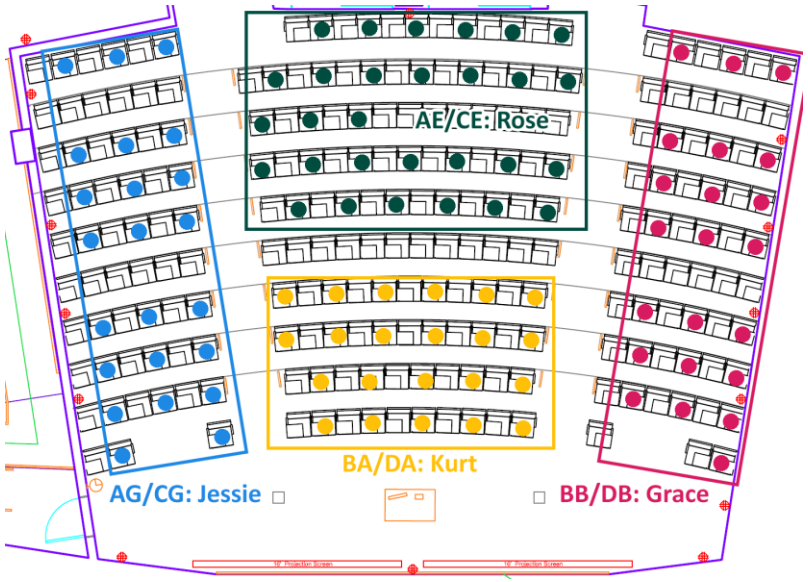
# Midterm Rooms and Sections

- Show up to space designated by your *registered* section!

## ARC 147




## CSE2 G20

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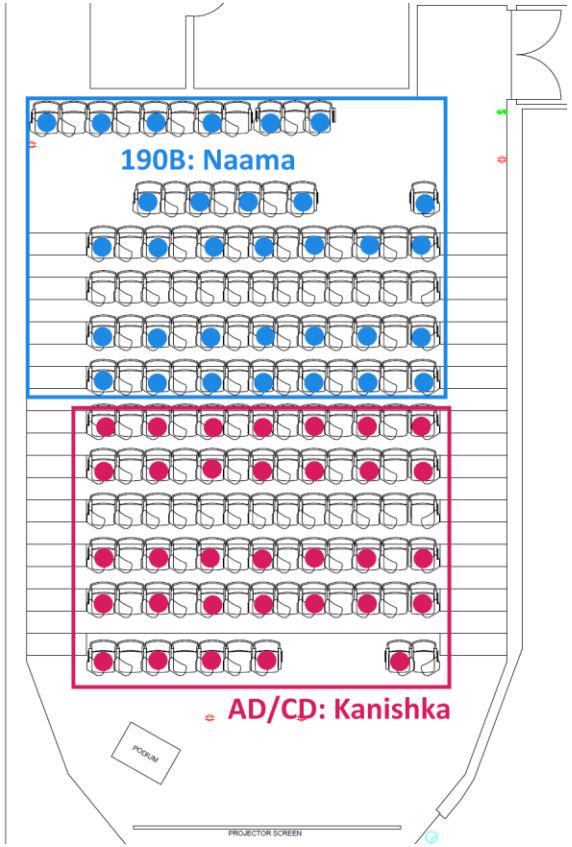


# Lecture Outline (1/2)

- **Structs and Typedef in C**
- Struct Layout and Alignment

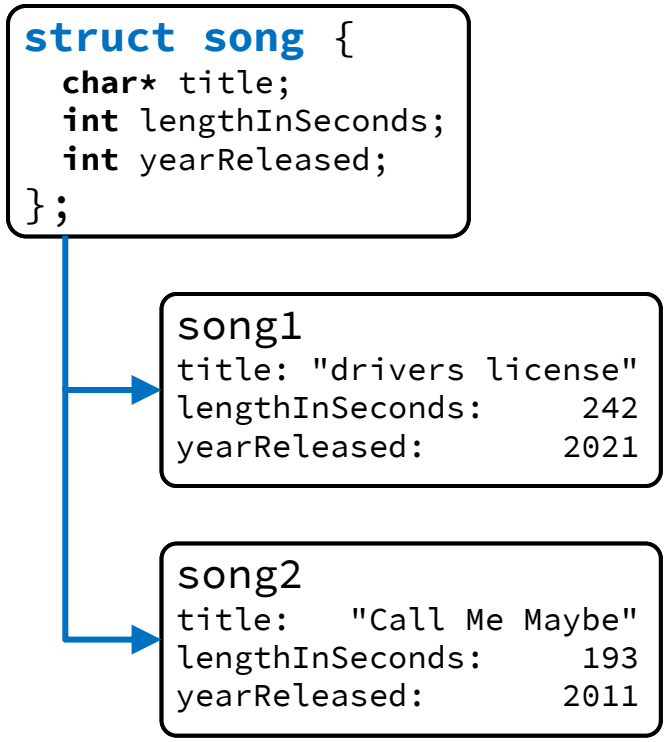
# Structs in C (Review)

- A structured group of variables, possibly including other structs
  - Way of defining compound data types

```
struct song {
  char* title;
  int lengthInSeconds;
  int yearReleased;
};

struct song song1;
song1.title = "drivers license";
song1.lengthInSeconds = 242;
song1.yearReleased = 2021;

struct song song2;
song2.title = "Call Me Maybe";
song2.lengthInSeconds = 193;
song2.yearReleased = 2011;
```



# Struct Definitions (Review)

- Structure definition:
  - Does NOT declare any instances
  - Creates new data type "**`struct struct_tag`**"

```
struct struct_tag {
  type_1 field_1;
  …
  type_N field_N;
};
```

Easy to forget semicolon!

- Variable declarations like any other data type:

```
struct struct_tag tag1, *pt, tag_ar[3];
```

instance pointer array

- Can also combine struct and instance definitions:
  - This syntax can be difficult to read, though:

```
struct struct_tag {
  /* fields */
} st, *p = &st;
```

# Scope of Struct Definition (Review)

- Why is the placement of struct definition important?
  - Compiler needs to know about this new symbol/data type
  - Without definition, program doesn't know how much space to allocate

```
struct data {
    int ar[4];
    long d;
};
```

← Size = **24** bytes

Size = **32** bytes →

```
struct rec {
    int a[4];
    long i;
    struct rec* next;
};
```

- Almost always define structs in global scope near the top of your file
  - Struct definitions follow normal rules of scope

# Typedef in C (Review)

- A way to create an *alias* for another data type:
  `typedef <data type> <alias>;`
  - After typedef, the alias can be used interchangeably with the original data type
  - *e.g.*, `typedef unsigned long int uli;`

- Joint struct definition and typedef:

```
struct struct_tag {
  /* fields */
};
typedef struct struct_tag alias;
alias a1;
```

```
typedef struct {
  /* fields */
} alias;
alias n1;
```

# Accessing Struct Fields (Review)

- Given a struct instance, access fields using the `.` operator:
  - ```
    struct rec r1;
    r1.i = val;
    ```
- Given a *pointer* to a struct:
  - ```
    struct rec* r = &r1;
    r->i = val;  // or (*r).i = val;
    ```

```
struct rec {
    int a[4];
    long i;
    struct rec* next;
} r1, *r = &r1;
```

- **In assembly:**
  - Holds address of the first byte in register (Rb) or label
  - Access fields with offsets (D)

```
# local struct
movslq  %edi, %rdi
movq    %rdi, -24(%rsp)
```

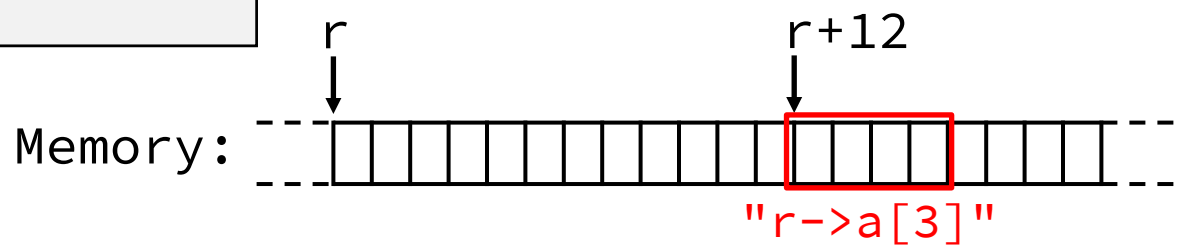
```
# global struct r1
movslq  %edi, %rdi
movq    %rdi, r1+16(%rip)
```

# Struct Pointers

- Pointers store addresses, which all "look" the same
  - Lab 0 Example: struct instance `Scores` could be treated as array of `int`s of size 4 via pointer casting
  - A struct pointer doesn't *have* to point to a declared instance of that struct type
- Different struct fields may or may not be meaningful, depending on what the pointer points to
  - This will be important for Lab 5!

```
int get_a3(struct rec* r) {
  return r->a[3];
}
```

```
  movl  12(%rdi), %eax
  ret
```



# Polling Questions (1/2)

```
struct ll_node {
  long data;
  struct ll_node* next;
} n1, n2;
```

- How much space does (in bytes) does an instance of `struct ll_node` take?

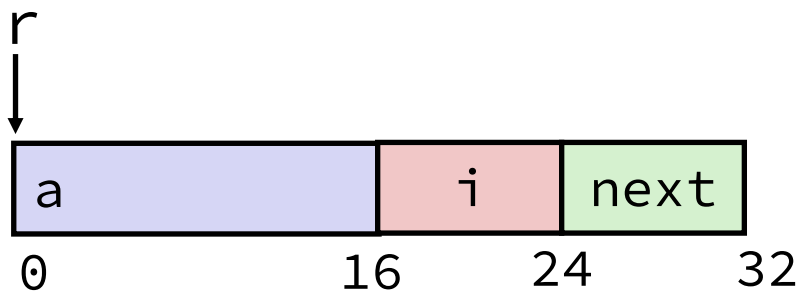
- Which of the following statements are syntactically valid?
  - `n1.next = &n2;`
  - `n2->data = 351;`
  - `n1.next->data = 333;`
  - `(&n2)->next->next.data = 451;`

# Lecture Outline (2/2)

- Structs and Typedef in C
- **Struct Layout and Alignment**

# Structure Representation (Review)

```
struct rec {
    int a[4];
    long i;
    struct rec* next;
} st, *r = &st;
```




- Structure represented as block of memory
  - Each instance is a contiguously-allocated region of memory big enough to hold all of the fields
- Compiler determines overall size + positions of fields
  - Fields ordered according to declaration order, even if another ordering would be more compact
  - Machine-level program has no understanding of the structures in the source code

# Alignment Principles (Review)

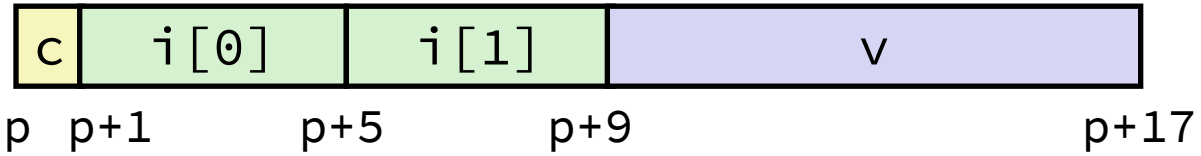
- Primitive data type of size $K$ bytes is considered *aligned* if its address is **a multiple of $K$**
  - Required on some machines; x86-64 hardware will work regardless
  - Memory accessed by aligned chunks of bytes (see: caching and virtual memory)
    - Inefficient to load or store value that crosses boundaries

- Address bit interpretation of alignment:

| $K$ | Type | Addresses |
|---|---|---|
| 1 | `char` | No restrictions |
| 2 | `short` | Lowest bit must be zero: $\ldots0_2$ |
| 4 | `int, float` | Lowest 2 bits zero: $\ldots00_2$ |
| 8 | `long, double, *` | Lowest 3 bits zero: $\ldots000_2$ |
| 16 | `long double` | Lowest 4 bits zero: $\ldots0000_2$ |

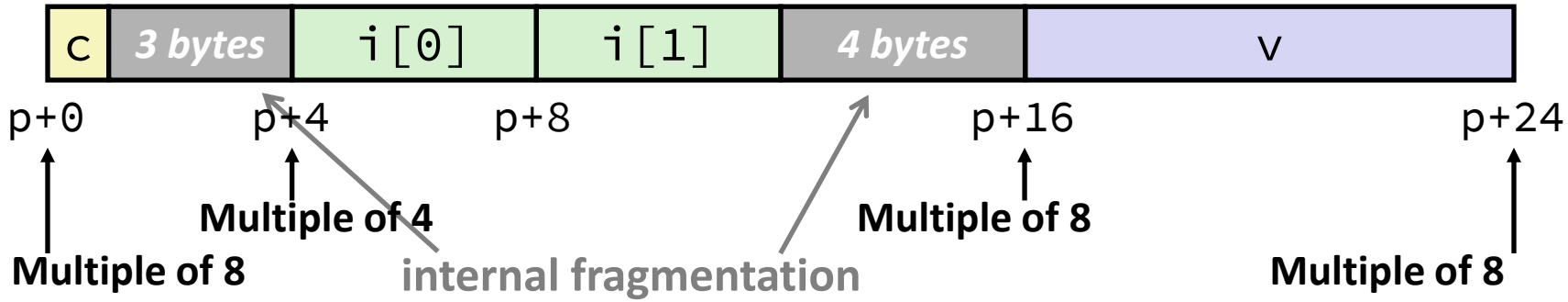
# Structures & Alignment (Review)

- Unaligned Data




```
struct S1 {
  char c;
  int i[2];
  double v;
} st, *p = &st;
```

- Aligned Data
  - Primitive data type of size $K$ bytes is considered *aligned* if its address is **a multiple of $K$**

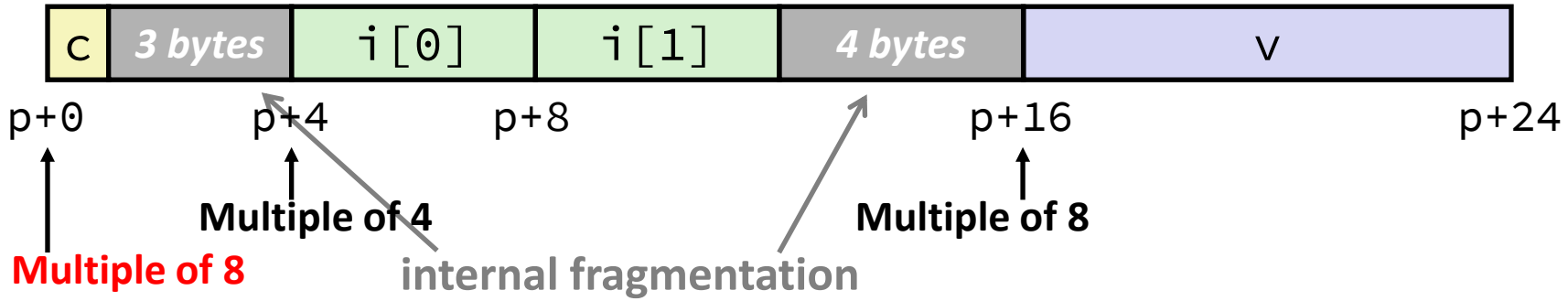


# Satisfying Alignment with Structures (1)

- Within struct we must satisfy each element's alignment requirement
- Overall structure placement has alignment requirement $K_{\max}$
  - $K_{\max}$ = largest alignment of any field

```
struct S1 {
  char c;
  int i[2];
  double v;
} st, *p = &st;
```

- Address of the struct must be a multiple of $K_{\max}$

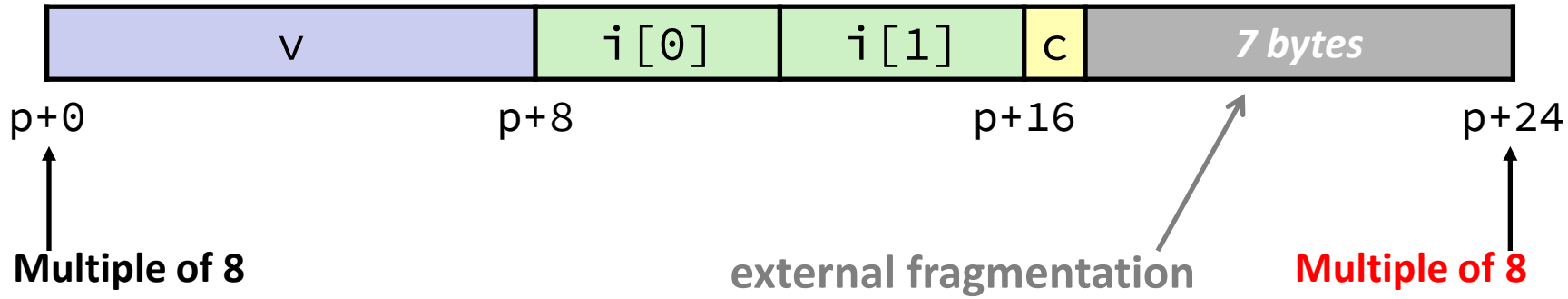


# Satisfying Alignment with Structures (2)

- Within struct we must satisfy each element's alignment requirement
- Overall structure placement has alignment requirement $K_{\max}$
  - $K_{\max}$ = largest alignment of any field

```
struct S2 {
  double v;
  int i[2];
  char c;
} st, *p = &st;
```

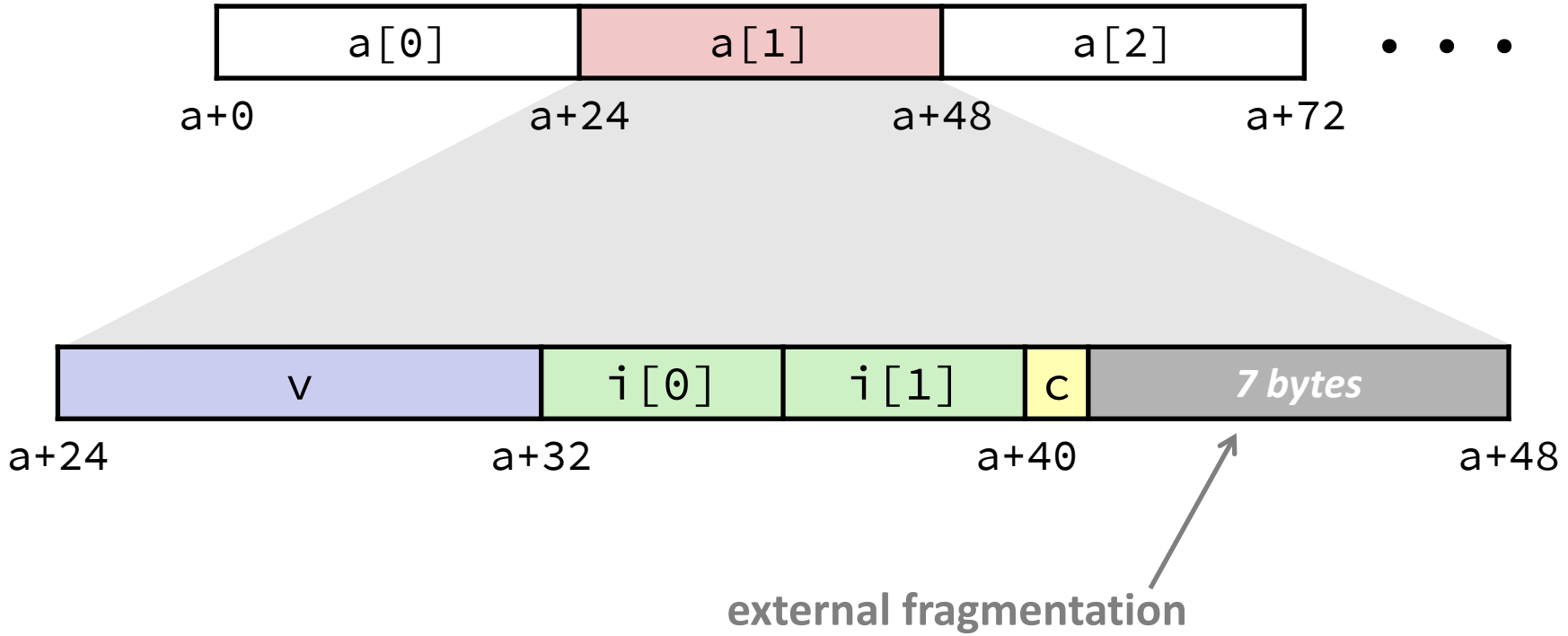
- Overall structure size must be multiple of $K_{\max}$



# Arrays of Structures

- Overall structure length multiple of $K_{max}$
- Satisfy alignment requirement for every element in array

```
struct S2 {
  double v;
  int i[2];
  char c;
} a[10];
```



# Alignment of Structs Summary

- Compiler will do the following:
  1) Maintains declared ordering of fields in struct
  2) Each ***field*** must be aligned within the struct to its $K$ *(may insert padding)*
  3) Overall struct ***size*** must be multiple of $K_{max}$ *(may insert padding)*
  4) When allocated, struct addresses will be ***aligned*** to $K_{max}$

- C Notes:
  - `sizeof()` can be used to get the overall size of structs
  - `offsetof()` can be used to get field offsets within structs

# Struct Layout Example (Review)

K
1
4
8
2

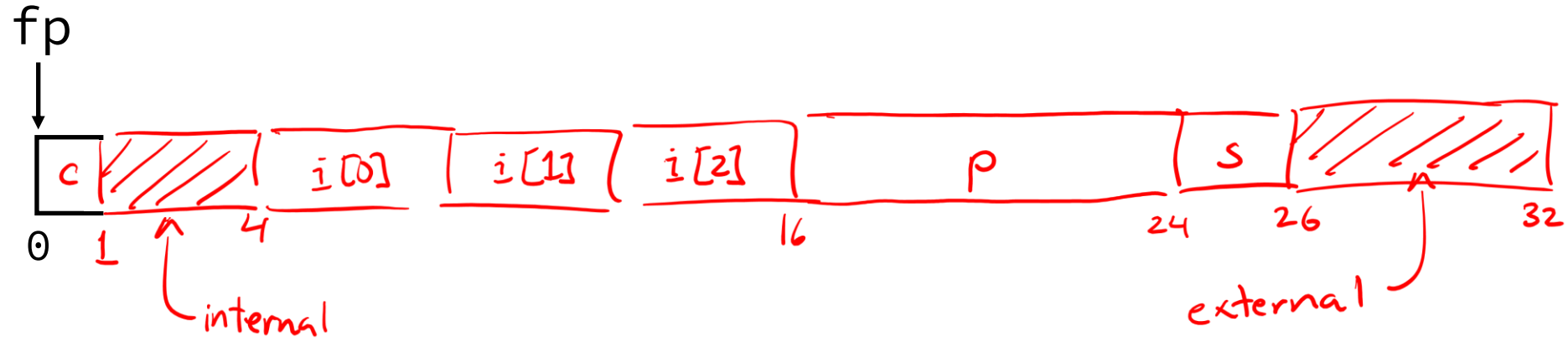
```
struct frag {
  char  c;
  int   i[3];
  struct frag* p;
  short s;
} f, *fp = &f;
```

$K_{max} = 8$

struct size = 32 B

internal fragmentation = 3 B

external fragmentation = 6 B

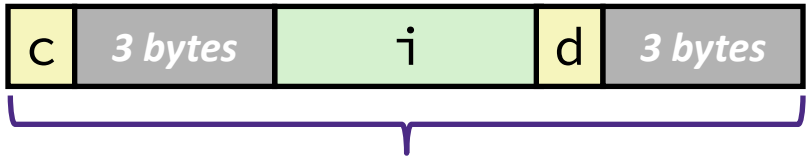


# How the Programmer Can Save Space

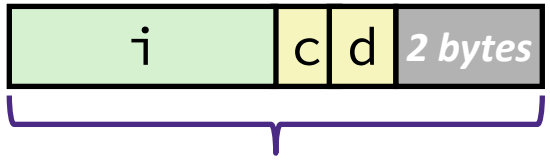
- Compiler must respect order elements are declared in
  - Rule of thumb: declare field in decreasing order of alignment requirement

```
struct S3 {
  char c;
  int i;
  char d;
} st;
```

```
struct S4 {
  int i;
  char c;
  char d;
} st;
```




12 bytes

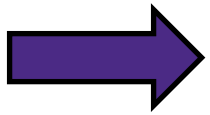



8 bytes

# Polling Questions (2/2)

- Minimize the size of the struct by re-ordering the fields:

```
struct old {
  int i;
  short s[3];
  char* c;
  float f;
};
```



```
struct new {
  int    i;
  _______ _______;
  _______ _______;
  _______ _______;
};
```

  - What is the minimum size of `struct new`?

    A. 22 bytes  B. 24 bytes

    C. 28 bytes  D. 32 bytes

# Homework Setup (if time)

- Struct in a struct?
  - It's just another data type, with its own alignment requirement
  - Example:

```
struct outer {
  char c;
  struct inner {
    short s;
    int i;
  } in;
};
```

→

```
struct inner {
  short s;
  int i;
};
struct outer {
  char c;
  struct inner in;
};
```

# Summary

- Alignment
  - Data of alignment requirement (*i.e.*, size) $K$ is considered aligned if its address is a multiple of $K$
  - Arrays have alignment requirement of an individual element, not the total size

- Structures
  - Allocate bytes for fields in order declared by programmer – can make choices to minimize memory allocations
  - Pad in middle to satisfy individual element alignment requirements ($K$)
    - ***Internal* fragmentation**
  - Pad at end to satisfy overall struct alignment requirement ($K_{max}$)
    - ***External* fragmentation**